PLASMA FOR-INJECTOR OF SEPARABLE MATERIAL BASED ON THE BEAM-PLASMA DISCHARGE FOR ION-ATOMIC SEPARATION TECHNOLOGIES. CONCEPTION

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In the paper, the functional definition of a plasma for-injector of separable material is presented, and the requirements to it are formulated. The version of a device for the material separation into elements based on the beam-plasma discharge is under consideration. The dimensions of a pilot separating device are determined. The following quantities are estimated: the particle concentration per unit length of the separating device, effective length of the beam-plasma interaction (BPI) within the separating device, dynamics of a plasma density increase for metallic uranium, and thermal characteristics of a phase transformation unit. A conclusion was drawn on the expedience and validity of the development and realization of a plasma for-injector for separating devices and technologies basing on the beam-plasma mechanism of formation and heating of a highly ionized plasma.

In the literature [1–3, 9], a possibility to use magneto-plasma separators (MPS) for the processing of nuclear waste and spent nuclear fuel was discussed. The idea of the processing consists in the following: a working material, spent fuel waste (SFW) or radioactive waste (RAW), is prepared for the introduction into a phase transformation unit. There the separable material is transformed from the solid (liquid) state into the vaporous state and then is introduced into a plasma source chamber for its ionization. Ions of the plasma formed, being in a magnetic filed, are selectively heated, which results in changing their flow path in a magnetic field, the spatial separation of "hot" and "cold" ions, and their deposition on ion-receiving plates, from which the deposited elements are removed. In addition, the plasma ions, from RAW or SFW, can be separated into light and heavy mass groups (the so-called "partial separation") or into separate elements ("full separation"). For the "partial separation", a problem consists in decreasing the specific dose of a radioactive part in the stored RAW excluding their complete processing.

In the operation of the plasma source (injector) based on the beam-plasma discharge taking place in MPS, one can distinguish several subsequently running stages. First, it is the stage of working material preparation in the required phase, namely, the vaporized state. The second stage intends the introduction (transport) of a separable material in the vaporized state into the ionization zone. The third stage is the ionization process (impact ionization by a linear law). Note that, in the case of the beam-plasma discharge, the ionization zone can be realized at any point of the separation volume (track), where the excess density of neutral particles of the separable matter of an order of 10^{12} cm^{-3} is created. The fourth stage is the ionization too; but, in this case due to collective processes, the density increases by a nonlinear (exponential) law. The fifth stage is specified by the heating of electrons and ions of the plasma formed in the beam-plasma discharge at the expense of the electron-cyclotron resonance (ECR) and the ion-cyclotron resonance (ICR). Thus, the multistage work of the so-called plasma source can evidence not simply the creation and operation of a plasma source but the creation and operation of a more complex and more functional device – a for-injector for filling the separator volume by a separable material in the neutral and ionization states at different time instants.

The main requirements to the plasma source (PS) should be formulated with regard for the MPS macroparameters (geometry, dimensions, magnetic field value, diagnostics at the phase of isotope separation), as well as the plasma microparameters (density, temperature, their fluctuations, spatial distribution, ion charge, rates of plasma rotation, plasma stability or instability). So, the main requirements are:

– plasma density at a level of 10^{10} – 10^{12} cm^{-3};
– plasma electron temperature $T_e \leq 50$ eV;
– ion temperature $T_i \approx 20$ eV;
– plasma stream value $n_p v_p s$ of an order of 1×10^{19} s^{-1};
– plasma stream velocity $(3 \div 5) \times 10^4$ cm/s;
– neutral flux into the separation zone no more than 3.5×10^{18} s^{-1}.

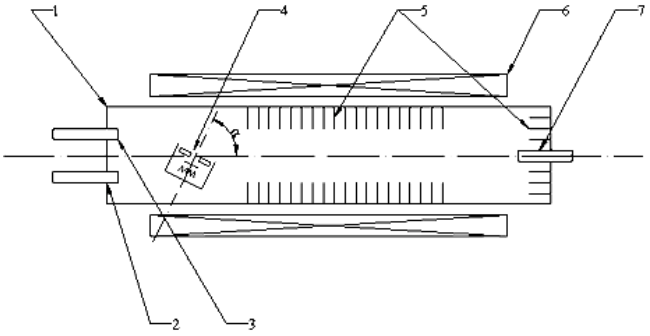

Fig. 1. Schematic presentation of the device for material separation into elements

Furthermore,
– ease of placing the ion-receiving plates (electrodes) for useful product collection;
– mode of operation – stationary or quasistationary;
– presence of a natural transverse E-field in the plasma;
– providing the useful ion yield onto the ion-receiving plates under operation conditions without introduction of additional electric fields and electrodes for their creation;
– possibility of reaching and maintaining the more uniform plasma density distribution across an MPS plasma chamber during the operating cycle.
– possibility of adjusting and controlling the physical parameters of a plasma source, namely, by changing its process variables.

The expected parameters of a pilot variant of the separating device can be as follows:
– plasma radius ~ 0.5 m;
– plasma column length (formation) ~ 4 m;
– plasma volume 3.14 m^3;
– plasma ion component density $\geq 10^{12}$ cm^{-3}.

Further calculations and estimations will be made with taking these dimensions and quantities into account.

The schematic diagram of the device separating the material into elements made on the base of the beam-plasma discharge is presented in Fig. 1 [4].

The device includes vacuum chamber *1* connected with separable material-feed unit *2* and igniting gas-feed unit *3*. In its interior, chamber *1* comprises a plasma source in the form of electron gun *4* and a plasma stream receiver in the form of plates *5*. The device is provided with magnetic system *6* embracing chamber *1*. At the end of vacuum chamber *1*, oppositely to the place of separable material-feed unit *2*, igniting gas-feed unit *3* and electron gun *4*, beam collector *7* is placed. In the device offered, the main physical mechanism of plasma formation and heating is the collective processes initiated by the BPI.

The total number of plasma particles N_{total} in the separator volume can be calculated by the formula

$$N_{\text{total}} = \int\limits_S n(r)ds(r) = \pi n_{\max} r_0^2 \frac{\gamma}{\gamma+2}, \qquad (1)$$

where n and $n_{\max}$ are the plasma density and its maximum, respectively,r_0 is the maximum radius of a plasma formation, and γ is the index characterizing the profile, i.e. the type of a spatial plasma density distribution. At $\gamma = 2$, the plasma density distribution $\frac{n(r)}{n_{\max}} = 1 - \left(\frac{r}{r_0}\right)^{\gamma}$ is parabolic; at $\gamma \geq 3$, it is close to the equilibrium one; and, at $\gamma < 2$, it is tapered to the periphery.

In [5], it is shown that, in the plasma formed as a result of the beam-plasma interaction development, the exponent γ as a function of charge parameters changes from 0.3 to 10. This evidences that the total number of particles in the discharge (in the separator chamber) can differ by a factor of 5–6 and more depending on the plasma profile. The maximum value of N_{total} can be reached at $\gamma \sim 10$, i.e. in the case of a uniform plasma density distribution across the plasma section. For the above-mentioned separator dimensions, the total number of particles per unit length of the separator is 0.39×10^{19} particle/m and 0.65×10^{19} particle/m for the parabolic plasma density distribution ($\gamma = 2$) and for the uniform distribution ($\gamma = 10$), respectively (see Fig. 2).

As is known [6], the beam-plasma discharge formation is critical to the interaction length. This is explained by the fact that there is the least length, at which the excitation of oscillations to the noticeable amplitude is possible. The minimum length, at which the beam dissipates its energy for the excitation of plasma oscillations, can be estimated by the formula [6]

$$L \approx \frac{v_0}{\gamma} \approx 10^{-8} \frac{E_e}{j} \sqrt{n_p}, \qquad (2)$$

where γ is the oscillation amplitude rise increment; v_0 is the directed electron velocity in the beam; E_e is the beam electron energy in eV; j is the beam current density in A/cm^2; and n_p is the plasma concentration in cm^{-3}.

The oscillation amplitude increases with the length of the electron beam-plasma interaction and, at some lengths, can reach the value sufficient for the additional gas ionization. Beginning from this length, a plasma-beam discharge occurs. Figure 3 shows the dependences

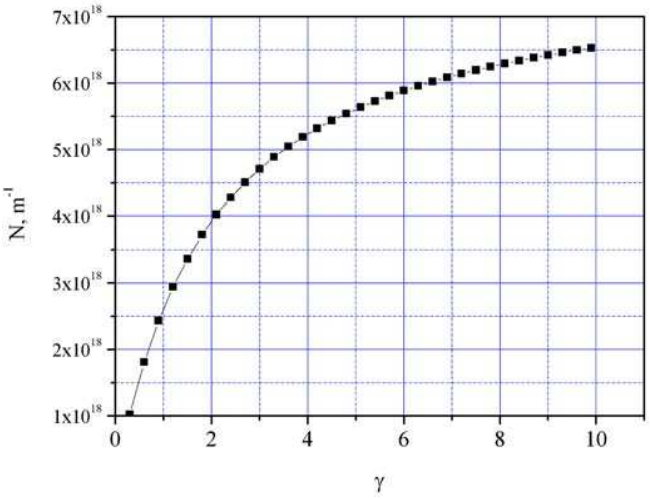

Fig. 2. Particle number per unit length of the separating device as a function of the index characterizing the plasma density radial distribution profile

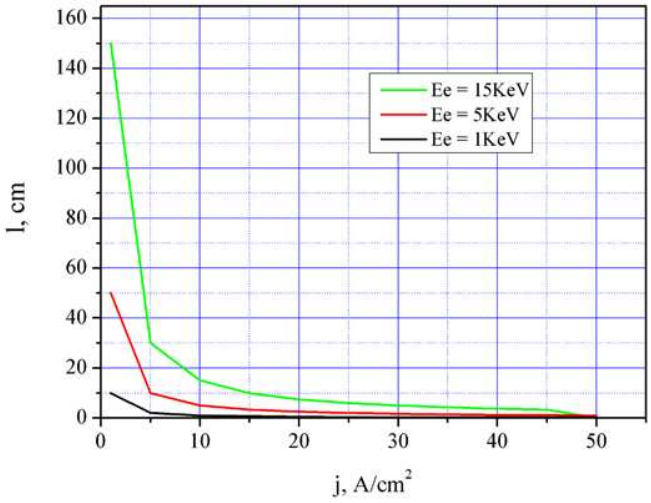

Fig. 3. Effective beam-plasma interaction length as a function of the electron beam current density for different energy values at a plasma density $n_p = 10^{12}$ cm^{-3}

of the effective BPI length on the electron beam current density in the range of $j = 0 \div 50$ A/cm^{2}at different values of its energy (1.5 and 15 keV) for a plasma density of 10^{12} cm^{-3}. It is seen that the calculated values of the effective BPI length are ranging from fractions of 1 cm to tens and hundreds of centimeters. For the really obtained electron beam current (10 – 20 A) at transverse dimensions $2R \approx 1$ cm, we have the current density $j \approx 10 \div 25$ A/cm^2 and, respectively, the interaction length $L \approx 10 \div 20$ cm. At higher current density values, for example ≤ 100 A/cm^2, the required interaction lengths are at the same level or a slightly decreased one.

Taking into account the literature data [7] on the ratio $r_p/r_b \approx 5 \div 10$ (r_p is the plasma radius, r_b is the electron beam radius), we obtain that, in the given project at $r_p = 50$ cm, the value of r_b should be not less than 10–15 cm. For this, it is necessary to obtain electron beams of a larger cross-section (of a large aperture) and, respectively, cathodes with a larger emitting surface 200–400 cm^2. Such an emitting surface can be obtained either in the form of a synthesized polyelement (mosaic) block or on the plasma cathode base [8]. At an electron beam current density of 1–2 A/cm^2, the power supplied for its formation is of an order of 1 MW. At the same time, the power of a RF-oscillator used for the realization of the project ARCHIMED is 8 MW [2].

The processes running due to the electron beam-gas (vapor) target interaction and leading to the dense plasma formation can be divided into two characteristic stages. At the first stage, the electron beam with density n_e and velocity v_e interacts with the neutral gas (vapor) of a density n_0, and, due to the impact ionization, a primary plasma with density n_p less or equal to the beam density is formed. The process of plasma formation at this instance of time is described by the equation

$$n_p = n_e v_e \sigma_e n_0 \tau, \tag{3}$$

where σ_e is the ionization cross-section of neutral particles with electrons, and τ is the plasma lifetime.

The degree of ionization is at a level of $\sim 10^{-2}$%, and the temperature is lower than the first ionization potential ($T_e < E_i$). The beginning of the second potential is characterized by the excitation of sufficiently powerful rf oscillations at the electron-cyclotron frequency [9]. The plasma electrons, being accelerated in the fields of these oscillations, reach the energy necessary for the further neutral gas ionization, and the increase of the plasma density is avalanche-like, the degree of ionization increases to 100%, and the density increases by the exponential law

$$dn_p = \langle \sigma_e v_e \rangle n_0 n_p dt, \tag{4}$$

where n_p is the current plasma density.

Here, it is assumed that the time of the plasma electron acceleration is much less than the time of the plasma density increase, and the plasma losses at $n \ll n_0$ are negligibly small. Such a statement is valid only for the instant of time $t \ll \tau$. Later on, the plasma density increase will be determined to a greater extent by the balance of the exponential density growth according to

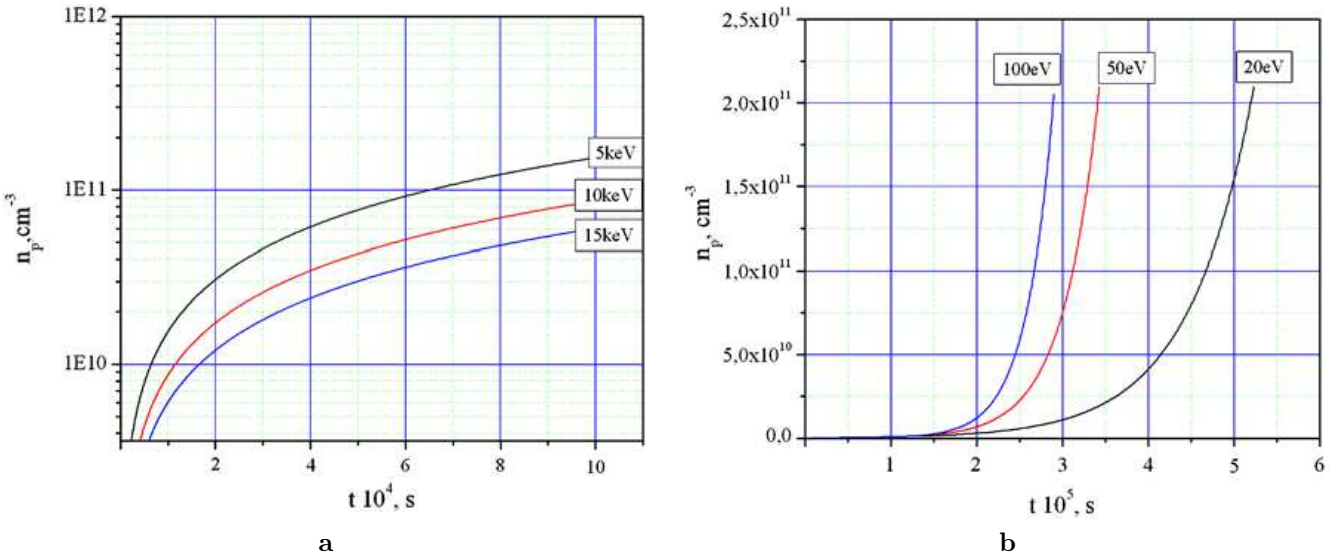

Fig. 4. Plasma density increase dynamics calculated for metallic uranium: *a* – linear stage of discharge; *b* – exponential stage of discharge

Eq. (4) and by the plasma loss. Among the processes leading to the plasma loss, the processes of plasma recombination and diffusion across the magnetic field and its runaway into the magnetic plug are dominant.

Figure 4 presents the calculated time dependences of the plasma density for the linear (*a*) and exponential (*b*) growth in the case of metallic uranium [10, 11] during its evaporation or corpuscular-plasma sputtering in the discharge zone. In addition, to evaporate a material, one can use the electron-beam evaporation, laser evaporation, flash evaporation [12–14]. An important feature of the electron-beam evaporation is that it can be realized in variants with or without crucible [13].

An important characteristic of the whole plasma source and its components is the energy expenditure for the realization of phase transformations of a separable material and its ionization. To determine the plasma source efficiency, we estimated the energy expenditures, the required working material mass consumption at a constant plasma stream, and the specific rate of material evaporation in the phase transformation unit for groups of metals, being of interest for imitation-separation experiments, as well as for the industrial and semiindustrial processing of RAW and SFW.

For the metal under consideration at a constant plasma stream at a level of 4.7×10^{21} particle/s, the values of the required material mass consumption m, specific rate of material evaporation a_V, evaporation temperature T_V, and melting temperature $T_{\rm mel}$ are given in Table 1.

The calculated values of the molar quantity of heat for the evaporation of selected materials (for UO_2, it is the molar melting heat), as well as the molar energy expenditures by electron-beam evaporation of Zr and U [15] are given in Table 2.

The use of BPI makes it possible to obtain the plasma with given parameters ($n_e \sim n_i \geq 10^{12}$ cm^{-3}; $T_e \geq 100$ eV; $T_i \geq 300$ eV) in large volumes ($\sim$ 1–10 m^3) of separating devices. The operation mode of the beam-plasma discharge can be pulsed (100–600 μs), quasistationary (1–1000 μs), or stationary (1–10 s and more).

The calculations show that the effective length of the primary electron beam deceleration is from tens of centimeters to several meters, which corresponds, in principle, to linear dimensions of separating devices and

Table 1

	$\dot{m}$, g/s	a_V, g/(cm^2×s)	T_V, K	$T_{\rm mel}$, K
Zr	0.719	1×10^{-2}	3189	2133
Bi	1.646	2.5×10^{-2}	1153	544
Pb	1.632	1.8×10^{-2}	1254	600.65
U	1.875	1.7×10^{-2}	2781	1408
UO_2	2.127	1.7×10^{-2}	2800	3123

Table 2

	$Q \times 10^{-5}$, J/mole	$E \times 10^{-7}$, J/mole
Zr	7.63	2.16
Bi	2.3	–
Pb	2.33	–
U	6.46	1.8
UO_2	3.78	–

keeps within the range of separation of elements or their isotopes.

The major advantage of the plasma formation method offered is the fact that the electron beam from an external source (electron gun) in vacuum and a longitudinal magnetic field propagates almost without losses at any distances within the limits of the above-mentioned values. That is, the plasma can be formed at any points of the transport track having the length of several meters, namely in the separation zone.

Another substantial merit of this method, as compared with the other plasma formation methods, is the evidence of that, in the mass composition of the plasma formed, only the particles (ions, neutrals) of the introduced working material are presented, and the plasma is not contaminated with particles from materials of electrodes, diaphragms, etc.

Under conditions of the beam-plasma discharge, it is possible to reach the 100-% neutral burn-up that is confirmed with the confidence in earlier experiments [16].

The realization of the beam-plasma discharge allows one to use different methods for the introduction of a working material, practically, at any point (into a region) of the injection track.

So, the beam-plasma mechanism of formation of a dense hot high-ionized plasma gives promise for the development and the realization of a plasma for-injector on its base, as well as its use in separating devices and technologies.

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ПЛАЗМОВИЙ ФОРІНЖЕКТОР РОЗДІЛЮВАНОЇ РЕЧОВИНИ НА ОСНОВІ ПУЧКОВО-ПЛАЗМОВОГО РОЗРЯДУ ДЛЯ ІОННО-АТОМНИХ СЕПАРАЦІЙНИХ ТЕХНОЛОГІЙ. КОНЦЕПЦІЯ

Є.І. Скібенко, Ю.В. Ковтун, В.Б. Юферов

Р е з ю м е

Наведено функціональне визначення плазмового форінжектора розділюваної речовини і сформульовано вимоги до нього. Розглянуто варіант пристрою для розділення речовини на елементи на основі пучково-плазмового розряду. Визначено розміри напівпромислового варіанта сепараційного пристрою. Оцінено концентрацію частинок на одиницю довжини сепараційного пристрою, ефективну довжину пучково-плазмової взаємодії в межах сепараційного пристрою, динаміку росту щільності плазми металічного урану, теплові характеристики блока фазових перетворень. Зроблено висновок про доцільність і обґрунтованість розробки і реалізації плазмового форінжектора для сепараційних пристроїв і технологій на основі пучково-плазмового механізму утворення і нагрівання високоіонізованої плазми.